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Portable Linear Sled (PLS) for Biomedical Research

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ABSTRACT

The PLS is a portable linear motion generating device conceived by researchers at Ames Research Center's Vestibular Research Facility and designed by engineers at Ames for the study of motion sickness in space. It is an extremely smooth apparatus, powered by linear motors and suspended on air bearings which ride on precision ground ceramic ways. (FIGURE 1).

INTRODUCTION

Bioaccelerometers in the inner ear sense head motion and orientation relative to Earth gravity. These sensors automatically control eye position during head motion to ensure stable vision. An important objective of NASA's Biomedical Research Program is to understand how this system adapts to weightlessness and re-adapts to Earth gravity on return from space. To achieve this objective, responses must be recorded during well-defined, well-controlled, noise-free (<.001 g) linear oscillations. Linear sleds to provide such accelerations to human and animal subjects already exist at Ames. The purpose of the present report is to present a description of a new portable linear sled (PLS) designed to be transported to a pre-launch and post-landing test-site in Russia for pre- and post-flight testing of rhesus monkey responses. The paper will focus on the mechanical design of the PLS, as well as the problems and solutions found during design and system development and deployment.

PROJECT REQUIREMENTS AND PERFORMANCE SPECIFICATIONS

This project required the design of an exceptionally smooth linear motion sled capable of distortion free sinusoidal motion. Unlike current Ames models which ride on large granite blocks, it had to be portable allowing it to be transported to different locations and to be carried and set up by hand. In addition, there were only 22 months to take the project from initial concept to operational status in Russia.

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The performance specifications of the PLS were derived from the needs of the Principal Investigators to have a linear sled capable of smooth, distortion free sinusoidal motion to:

- Prevent "cueing the test subject that a change in direction had occurred or was about to occur.
- Allow the use of simple single frequency Fourier analysis vs. more rigorous analyses that would be required if distortion or non-linearities were present.

Distortion and noise levels were not to exceed .001g. This requirement was dictated by the science community as being just below the threshold of perception of human and animal subjects and therefore, necessary if the data was to be free of ambiguity. It encompassed all noise and vibration caused by the PLS structure, drive system and controls. Vibrations coming from the site locations or installation (external sources) are not included in the .001g noise limit requirement.

The drive system is designed to requirements for generating sinusoidal acceleration with a peak value of 1 g at frequencies ranging from 1 to 5 Hz. Maximum peak to peak travel of 20 inches occurs at 1 Hz and 1 g. Peak to peak travel at 5 Hz and 1 g is .8 inches. It was also required that the system be capable of either horizontal of vertical operation. (FIGURES 1 and 2).

DESCRIPTION OF THE PLS SYSTEM-MECHANICAL

The PLS consists of an air bearing supported, linear motor driven carriage. Trunnion mounted to the carriage is a capsule designed to accommodate a rhesus monkey. When operating vertically, the 650 lb. weight of the carriage and capsule are balanced by an air powered equilibration system. This system consists of 95 psi air applied to a 3" diameter piston. The piston and it's cylinder reside along the central axis of a 7" diameter by 84" long reservoir cylinder. Air is ported from the reservoir into the pressure side of the piston. A 1/2" diameter polished steel rod is connected to the piston. It passes through a seal and is, then, joined to a 1/4" diameter wire rope, routed over two sheaves and connected to the carriage. (FIGURE 2).

The reservoir in pressurized until the weight of the carriage and capsule are exactly balanced at the mid-travel position. The ratio of displaced volume to total system volume is such that the pressure balancing force variation (even for the 20 inch travel) is just over 2.5% at the travel extremes.

Similar air equilibration systems, which greatly ease motor control, have been used successfully for many years in aircraft motion simulators at Ames.

The capsule position on the carriage can be oriented about three independent axes. The monkey's behavior is monitored as it is taken through a

program consisting of many sinusoidal acceleration profiles with different capsule orientations in both the horizontal and vertical operating configurations.

The interior of the capsule can be completely blacked-out during motion generation or the cover over a large window directly in front of the subject's head can be removed. A point-light source is also used in the studies with the window covered.

Referring to FIGURE 3, the portion in the lower center of the figure is called the "backbone". It consists of two roughly 6"x12"x84" long, honeycomb structures bolted to the sides of the rectangular aluminum structure housing the equilibrator assembly. To the upper surface on each side of the backbone are bolted the hollow, ceramic rails (or ways) on which the air bearings ride. Also bolted to the backbone are the motor coil assembly, and the "foot" which supports the entire system when operating in the vertical mode. The carriage itself, which resembles a reclining capital "E" in cross section in the figure, is also a honeycomb structure. It is made in two, roughly "C" shaped sections for portability and joined along the centerline at assembly.

The ceramic rails were manufactures by Wilbank Division of Coors brewing company, at Portland, Oregon to specifications dictated by the PLS project engineers. Each rail consists of two, roughly 6" square by 1/2" wall by 84" long, aluminum oxide ceramic tubes. After firing, the sets of tubes were bonded together and all outside surfaces were ground to a 16-20 micro-inch finish. Once they are fired, the rails can only be machined using diamond tools. The very low "flying height" of the air bearings requires that the surfaces of the rails be extremely smooth and flat. Flatness, parallelism and perpendicularly were held to less than 0.001" over their entire length and the flatness, over any 6" length of the surfaces, was held to less than 30 millionths (0.000030) of an inch.

One half inch thick ceramic plates were bonded into place to close the tubes and a number of holes were bored through both the upper and lower surfaces so that tubular, ceramic inserts could be bonded into place for mounting the rails to the backbone.

The air bearings are state-of-the-art and operate with a flying height of only 0.0003". They are 5.6" in diameter and about 3" high. Two different configurations are used, ball joint mounted and rolling diaphragm mounted units (FIGURE 4). The two types of bearing assemblies are mounted in opposed sets. The ball joint mounted types establish the position of the carriage relative to the rails and the rolling diaphragm type permit tiny variations in the rail thickness. Both types allow for the minute variations in parallelism and perpendicularly. The minimum pressure required to float the carriage is about 25 psi. The optimum pressure, from the standpoint of system stiffness, is 56 psi.

Only the rail on the left side in FIGURE 3 is used to guide the carriage parallel to the motor axis (in the horizontal plane). Counterweights

approximately equal to the mass or these bearings are added to the carriage on the opposite side to maintain mass symmetry about the motor thrust axis.

Both rails are used to support the dead weight load in the horizontal operating mode and to react the overturning moment in both the vertical and horizontal modes.

A light weight gantry crane was designed, built and shipped to Russia with the rest of the equipment so that it could be used to unload equipment and to erect the 2000 pound PLS into the vertical operating position. The very tight schedule did not permit time even to try out this system at Ames. After a few bugs were ironed out, though, it worked very well at the Russian site. (FIGURE 5).

ELECTRICAL-ELECTRONIC

The drive system for the PLS consists of a brushless DC, 3-phase, linear motor, with a total stroke (displacement) greater than 20 inches; a 3-phrase, Pulse-Width-Modulate (PWM) power amplifier using an optical position encoder to generate the commutation switch-over commands; and an isolation transformer which could operate from 3-phrase 380 volt, 50 Hz supply or from a 3-phrase 480 volt, 60 Hz supply.

The motor is comprised of a configuration of eight coils and four permanent magnet assemblies (referred to as 'magnet tracks'). Two coils are aligned end-to-end in each magnet tract with four of these, two coil, assemblies arranged in parallel (FIGURE 6). The eight coils are each 5-pole, 3-phase units with a thrust coefficient of 20 pounds per amp.

The coil configuration was chosen to permit up to 640 pounds of sliding weight to be accommodates without causing over-heating problems. The 32 amps required to accelerate the 640 pound mass to one g requires only four amps per coil. With the heat load reduced it became possible to air cool the motors and to avoid water cooling and the operational problems that water would create.

The coil assemblies are constructed entirely of non-ferrous materials which permits operation without the 'cogging' effects which occur when a ferrous material enters or leaves the magnetic field surrounding a permanent magnet. This cogging effect can cause unwanted accelerations far in excess of the one milli-g smoothness required for the PLS's motion.

The coil assemblies are fixed and the magnet tracks are required to move as part of the carriage assembly payload. The coils weighed no more than a pound or so each and the magnet track assembly weighs over one hundred pounds, so from the standpoint of reducing payload weight it would have been better to reverse the situation. However, mounting the coils and moving the magnet tracks permitted hard wiring the stiff, heavy, power cables

and mounting the bulky air cooling lines rigidly to the backbone and this advantage was deemed far more important than the payload weight consideration.

The maximum displacement of the carriage is 20 inches peak-to-peak (at one g and one Hz, as mentioned earlier). The magnet tracks had to be long enough to permit this motion and still have the coils contained within a uniform magnetic field. The coil length is 12.4 inches and since there are two coils, end-to-end, in each magnet track, this requires a magnet track length of 48 inches. (FIGURE 6).

The control system for the PLS is a Digital Signal Processor (DSP) based, digital controller card located on the bus of an IBM compatible PC. The DSP controller card accepts position feedback from the carriage of the PLS, compares the coded position against the desired acceleration, and generates a command for the motor drive amplifier which will achieve the desired condition. The desired acceleration waveform is generated by the digital controller from the frequency and amplitude commands input by the operator to the control program for the particular test to be run. The actual waveform is obtained from the optical position encoder located on the carriage.

The controller operating software was successful in generating an operating scenario which allowed frequencies of 0.25 Hz to 10Hz to be generated at acceleration levels (g-levels) of 0.005 to 1.0 g, were run in Moscow to simulate space craft motions at the request of the Russian investigators. The PLS performed these loadings without any difficulty.

A separate, stand-alone safety system is used which continuously monitors the performance and operating conditions of the PLS and ensures that unsafe conditions are not allowed to persist. The safety system monitors motor coil temperature, air-bearing supply pressure, carriage position limits, carriage over-speed, power amplifier conditions, motor current limits and motor set-up procedures. Movement is not permitted to begin if any of these parameters are in an unsafe condition. If unsafe conditions occur during operation, the safety system will initiate a programmed shutdown while maintaining safe deceleration characteristics.

DESIGN PROBLEMS AND SOLUTIONS

The motor that was finally selected (manufactured by Trilogy Motor Company of Webster, Texas) was the third in a series of candidates for the job.

All linear motors have extremely high attractive forces between magnet and coil elements. In the standard, single interface configuration, used by the other motor candidates, it would have been required that these forces be reacted by the air bearings. At maximum motor thrust the attractive force can reach 3000#. This is approximately three times the design capacity of the bearings. An attempt was made to design around the problem using a second

motor candidate which promised slightly lower attractive forces, but without much success.

In the Trilogy motor design, the magnets are arranged on either side of the coil in a strong "U" shaped frame so that the attractive forces are balanced and there is no net reaction which must be carried by the air bearings. Needless to say, the introduction of this motor design was a real high water mark in the design process.

Like the motors, the rails are the third in a series of candidates designed to fill their function. The first set of rails was designed around the capabilities of an exclusive manufacturer of furnace brazed, aluminum foam composites. Each rail was to be made in three sections (because of the size limitation of the brazing furnace) and joined end-to-end. The air bearings were to operate on either side of the splice between two sections. Each section was to be ground and lapped to the final dimensions and finish. Unfortunately, the manufacturer of this system was unable to guarantee delivery of the finished product in a time frame which was compatible with the schedule for developing the PLS.

The second set of rails was based on an aluminum honeycomb composite structure. Finishing was to be done in the same manner as the first system, except that, without the constraint imposed by a brazing furnace, it was decided that they could be made in single, 84" long units. However, when the air bearing designer-fabricator was made aware of the change from three short sections to one long one, he strongly advised against it on the grounds that the grinding and lapping would be prohibitively time consuming and expensive. He recommended the ceramic rail approach which was finally developed for the PLS.

The extremely tight schedule for developing and checking out the PLS required that the motors and control system be tested in a parallel effort with the manufacture of the air bearings, rails and carriage structure. In order to do this a system (shown in FIGURE 7) was devised to simulate the configuration and mass of the PLS. This relatively inexpensive rail and ball bushing system was very stiff in the drive plane. Obviously, it couldn't be made nearly as smooth and friction free as the air bearing system, but it was adequate for motor check out and for control system and software de-bugging and refinement. The upside-down arrangement shown in the figure eased mounting problems and did not effect the performance.

IMPORTANT CONSIDERATIONS IN AIR BEARING DESIGN

The most important reasons for choosing air bearings over more conventional rolling or sliding bearings are as follows:

- To reduce friction
- To increase life
- To reduce mechanical noise

- To increase accuracy
- To provide the ability to dampen mechanical resonances

The first three items are guaranteed by the non-contacting nature of air bearings. With regard to the fourth item, air bearing systems have been designed for dimensional control down to the micron range. The last item was especially important to the development of the PLS because the requirement for light weight structures severely limited the amount of stiffness that could be built into the system. Air bearings can be designed with tuned internal cavities and restrictors such that particular frequencies can be selected or avoided. Space does not permit a detailed discussion of exactly how this is accomplished. A number of factors such as bearing gap and diameter, rail smoothness and flatness, laminar flow quality, flow restrictor type, etc., must be taken into account in this process.

In a system with near perfectly parallel rail surfaces, all bearings could be of the fixed gap (ball and socket) type. These systems are approximately 40% stiffer than the one used in the PLS. However, the requirement for relatively inexpensive, light weight rails demanded that they be less accurately made and, therefore, that a pre-loading device be used in half of the units as discussed earlier. The rolling diaphragm units are much easier to install and adjust than fixed spring type pre-loaders and have a much lower risk or resonance.

OPERATING RESULTS AT NASA-AMES

The PLS system was assembled at Ames and checked out completely for horizontal operation in July '92; two test subjects were run at 0.1, 0.3, 0.35 and 0.5 g-levels at all integer frequencies from 1 to 10 Hz. The PLS system was judged to perform satisfactorily and to meet the system test objectives even with a few deficiencies present.

The most obvious deficiency was the acoustic noise present when operating at high amplitude displacements and frequencies. However, since this acoustic noise was several hundred Hz's higher frequency than the data bandwidth, it was concluded it would not affect the test results and no further effort was made to eliminate it.

OPERATING RESULTS IN RUSSIA

The location of the operating lab in Russia was changed from the second floor room previously designated; it is on the ground floor and, fortunately, slightly larger than anticipated. The floor is not as rigid as the one at Ames. It is, however, much more rigid than the floor of any room on the second floor would have been. The larger room, (particularly the higher ceiling) reduced the acoustic coupling into the accelerometer used to measure the PLS's performance. The acoustic noise is approximately 10dB greater than that

achieve at Ames. A 15-20 dB increase in harmonic distortion was due two factors:

- The floor in Russia is much more compliant than the floor at Ames.
- The AC power line frequency of 50 Hz is less well conditioned and regulated than that at Ames.

The increase in harmonic content is more noticeable at 0.5 g level and higher; therefore 0.5 was selected as the maximum g- loading to be used. However, since the Russians did not want to expose the test subjects to g-levels higher than 0.5 g anyway, for fear of instrument failures, this limitation did not represent an additional constraint.

As mentioned earlier, the Russian investigators requested that the PLS be used to simulate the motion environment of the spacecraft in orbit. This required that it operated at frequencies as low as 0.25 Hz and at acceleration levels as low as 0.005 g. The PLS was not designed for, and was never operated (at Ames) at these, ultra-low g-levels and frequencies. However, the system performed without problems except that the accelerometer used to measure and display sled performance (but not used for control purposes) does not have sufficient dynamic range to measure accurately these ultra-low levels. The low frequencies did not degrade the performance of the accelerometer as did the low amplitude of acceleration. The accelerometer incorporates a nul-balance servo system which has DC (or zero Hz) frequency response. A different signal conditioner will have to be used if these ultra-low loading are to be repeated in an effort to obtain higher signal amplitude outputs to improve the signal-to-noise ratio.

RUSSIAN PROBLEMS IN RUSSIA

The machine and its support equipment were shipped to Russia in a total 16 large, heavy crates. Three weeks of intensive labor for three to five people was required in order to set up and check out the sled at the site. The change of location of the lab from the second to the ground floor helped, but certainly did not eliminate, the serious, hand-powered logistic problems. A method of lifting and transporting the heavy elements of the machine and the electronic racks and other heavy, bulky equipment had to be built and checked out in advance and shipped over with the machine (FIGURE 8). At the site, a method of providing about 40 feet of rolling surface from the nearest paved road to a door in the side of the building had to be devised so that equipment could be moved from the parking lot, staging area into the room which became the operating lab. (FIGURE 9).

Virtually everything that was required to set up and operate the equipment in Russia had to be shipped over. All tools, fasteners, adhesives, power cables, grout and mortar, even paper towels and toilet paper had to be sent over because these things are simply not available there. Even the

compressor to supply air to cool the motors and to float the air bearings had to be sent over because "shop air" was practically unheard of. Bottled air was available but in short supply and it was determined, in tests at Ames, that operating the PLS required one bottle of compressed air about every twenty minutes.

The compressor is powered by a 23 horsepower, gasoline engine. The noise and exhaust problems required that it be located outside the main building. The Russian winters and the possibility of losing the precious battery and fuel tanks required that the compressor be in its own, securable building. An assemble-in-place metal building had to be sent over with all the rest and a foundation had to be devised to set it up on. (FIGURES 10 and 11).

The lab at Ames was near clean-room quality. The room at the Institute for Biomedical problems in Moscow left a great deal to be desired from the cleanliness standpoint. The floor consists of terra cotta tile which had been applied directly to an earthen floor with mortar which varies from 1/2 to 1" thick. As a result, about 10% of the tiles are loose in their sockets and produce a constant stream of gritty dust as they are walked on. Repairs were made to the worst areas of the floor at the time the pads for mounting the machine were poured. However, the room remains dirty and dusty despite repeated wiping and vacuuming. This situation probably caused the air bearing "crash" experienced mid-way through the pre-flight test program. Replacement of the air bearing and repair of the ceramic rail was very expensive and difficult to accomplish without serious interference with the test schedule.

SUMMARY AND CONCLUSIONS

In spite of all the hazards and difficulties, the operation has been very smooth and, for the most part, trouble free. As of the present writing, all pre-flight testing has been completed.

The concern on the part of the Russian staff over the possibility of test subject instrumentation failure precluded testing in the vertical configuration. However, the machine was operated in that mode for the first time at the Moscow site and it performed extremely well. There is still a possibility that vertical testing will be performed after all other, post-flight tests are completed, since instrumentation failure at that point would not have disastrous consequences. Vertical operating capability will, no doubt, prove invaluable in future tests, both here at Ames and at other, more remote sites.

The space flight is currently scheduled to begin on December 29, 1992. And post-flight testing will begin immediately after the landing 10 to 14 days later.

ACKNOWLEDGMENTS

We wish to express our thanks to Paul Reeves of Six Degree Consultants, Menlo Park, CA, who developed the air bearings and tailored them to this particular application. Without his expertise and general knowledge in the air bearing field, it is doubtful the project could have been completed on schedule, if at all.

We would also, like to express our thanks to Marty Smith, Roger McKee and the rest of the staff of Micro-Craft, Inc., Tullahoma, TN who acted as general contractor for the final drawings and fabrication of the system.

This work was partially supported by NASA Space Medicine Tasks 199-16-12-17 and -19, and 199-90-63-20.

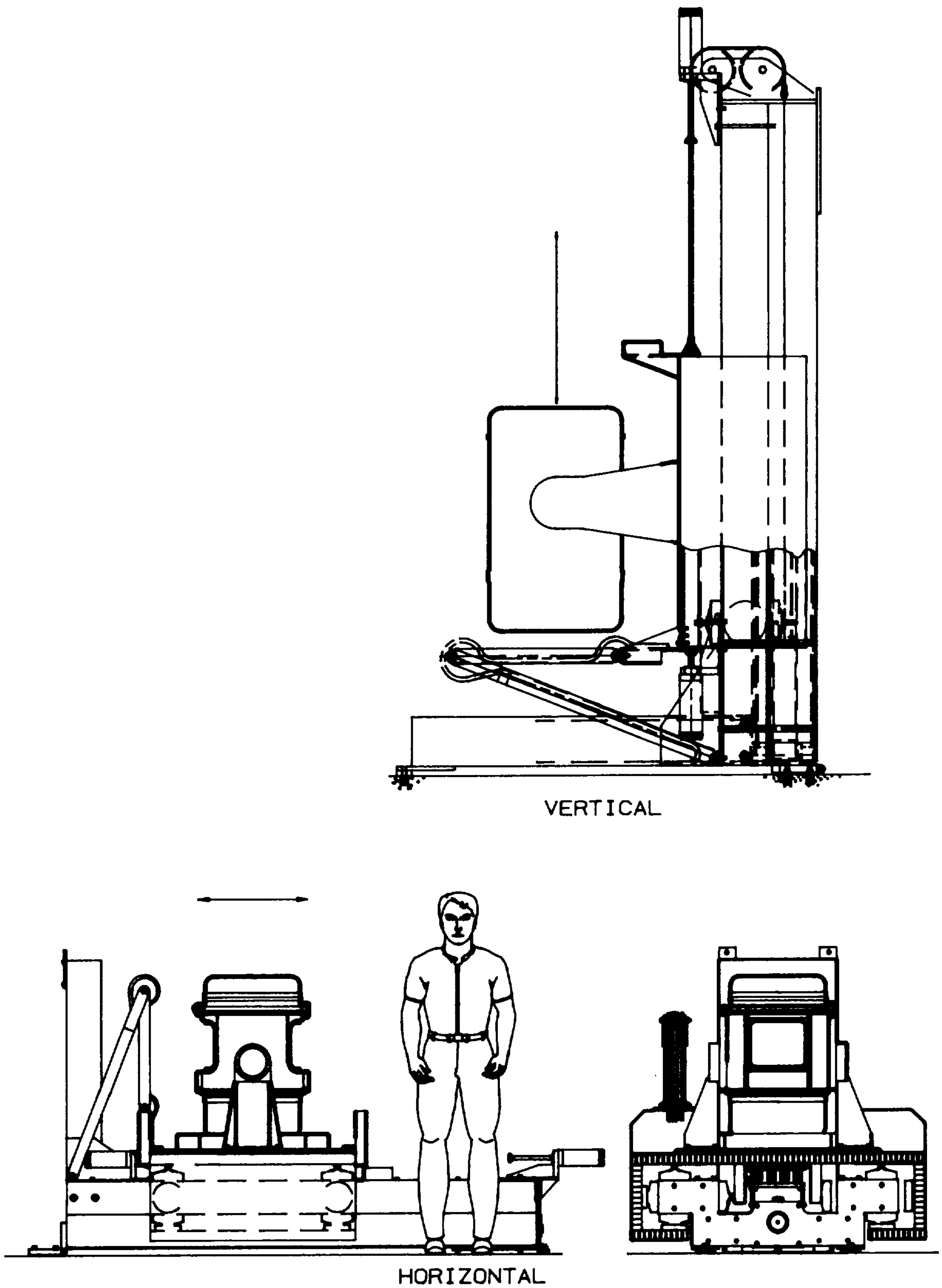


FIGURE 1 OPERATING CONFIGURATIONS

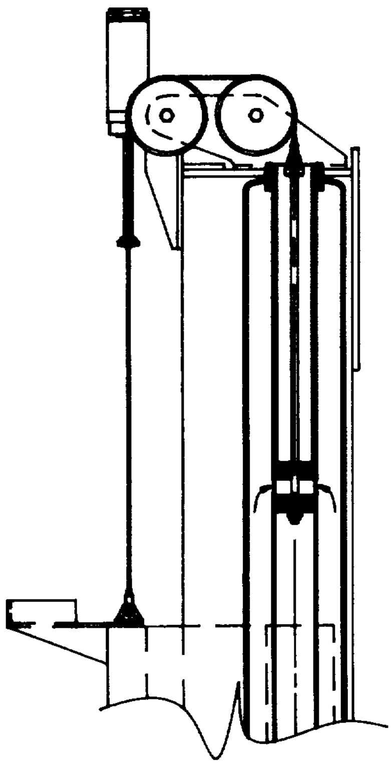
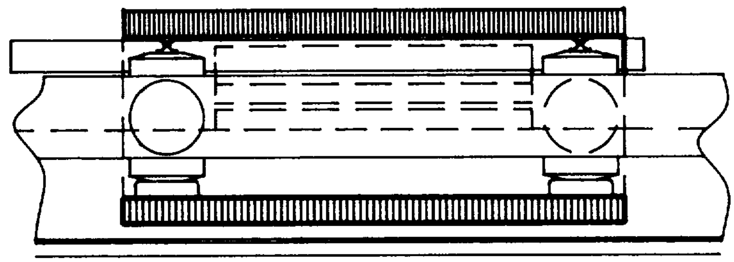


FIGURE 2 EQUILLIBRATION SYSTEM



CARRIAGE TRAVEL ELEMENTS
(SIDE)

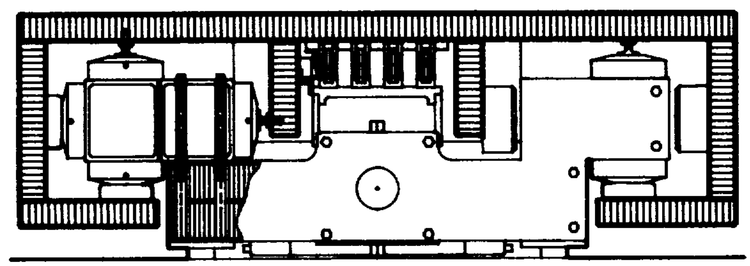


FIGURE 3 CARRIAGE TRAVEL ELEMENTS
(FRONT)

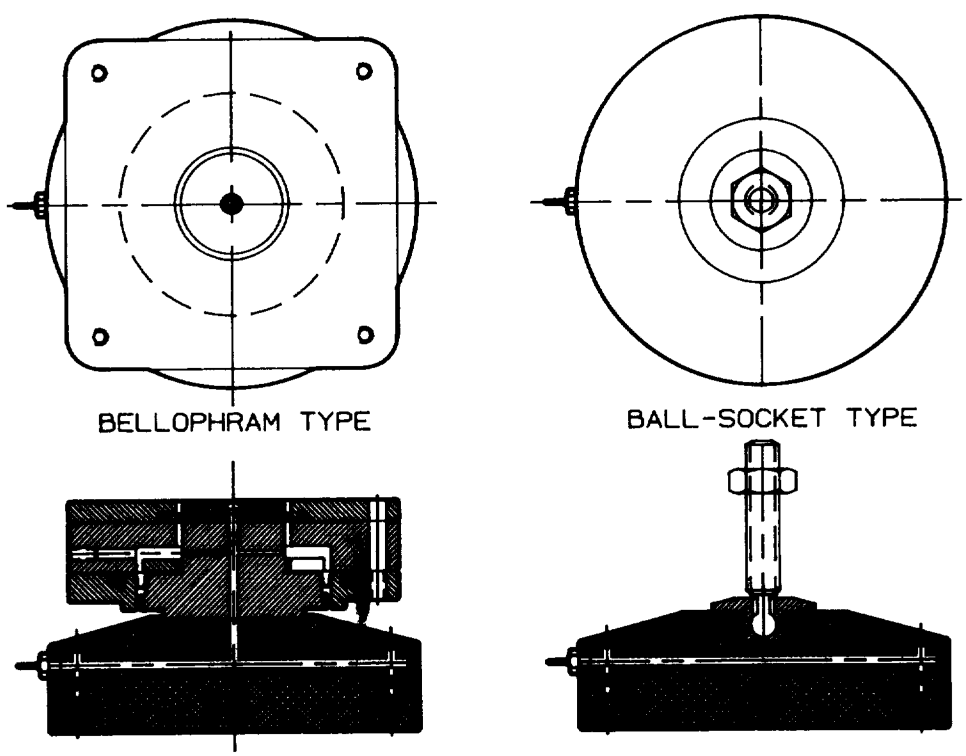


FIGURE 4 AIR BEARING CONFIGURATIONS

TABLE I
PLS MOTION

FREQ Hz	ACCEL g	DISPL IN-PK	VEL IN-PK/SE	
0.25	0.005	0.783	1.230	
0.3	0.01	1.088	2.050	
0.3	0.02	2.175	4.100	
0.5	0.005	0.196	0.615	ULTRA-LOW
0.5	0.01	0.392	1.230	RESPONSE
0.5	0.02	0.783	2.460	
0.5	0.04	1.566	4.920	
0.6	0.01	0.272	1.025	
0.6	0.02	0.544	2.050	
1	0.1	0.979	6.150	
1.5	0.1	0.435	4.100	
1.5	0.35	1.523	14.349	NORMAL
1.5	0.5	2.175	20.499	RESPONSE
5	0.1	0.039	1.230	
5	0.35	0.137	4.305	
5	0.5	0.196	6.150	

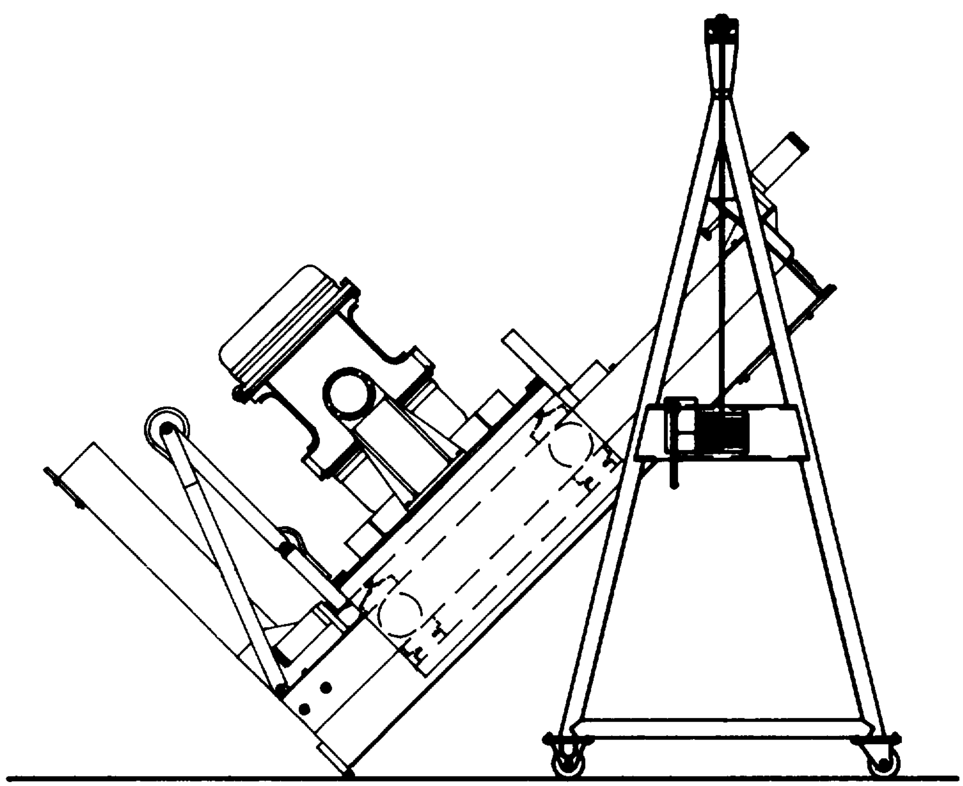


FIGURE 5 ERECTING FOR VERTICAL OPERATION

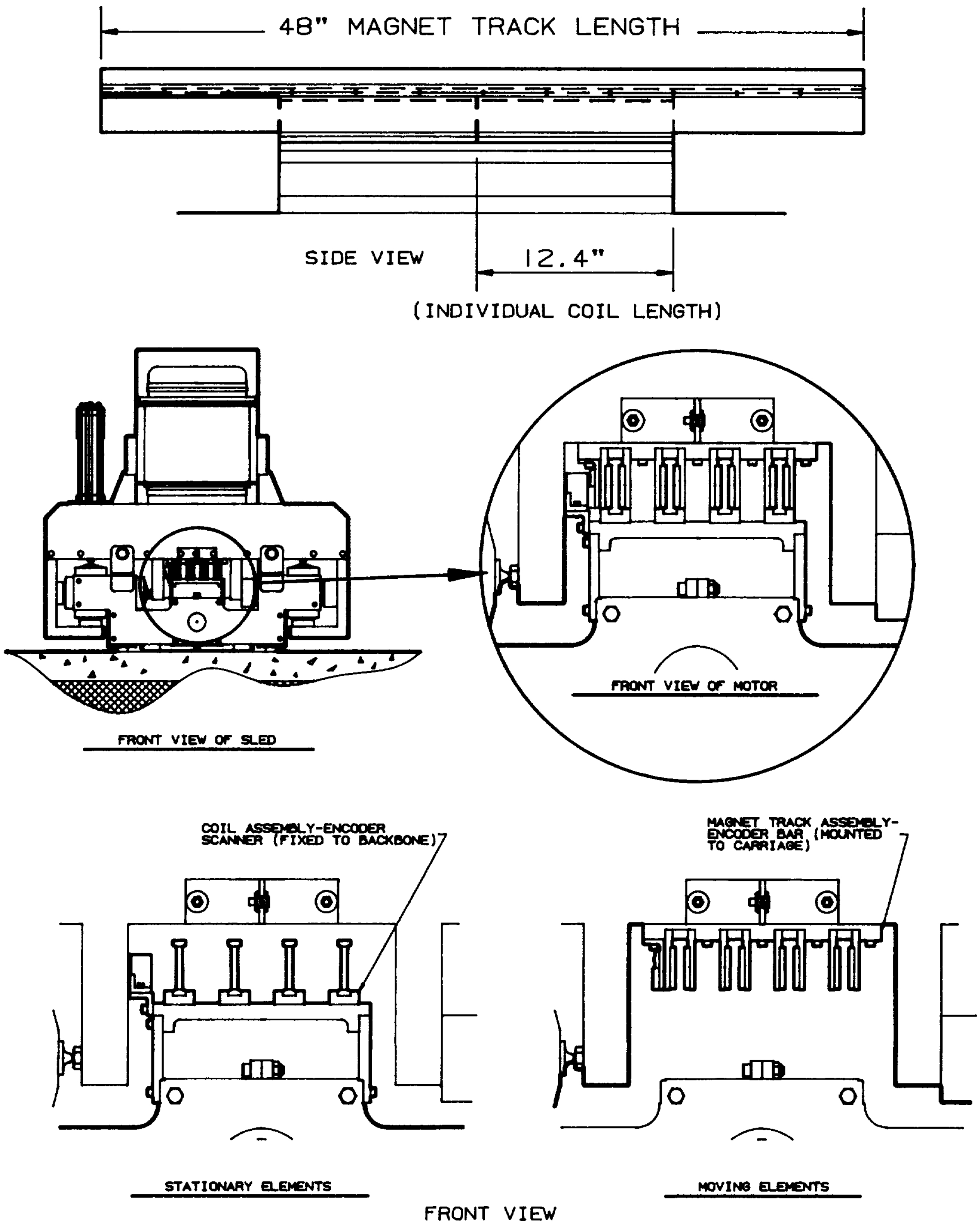


FIGURE 6 MOTOR CONFIGURATION

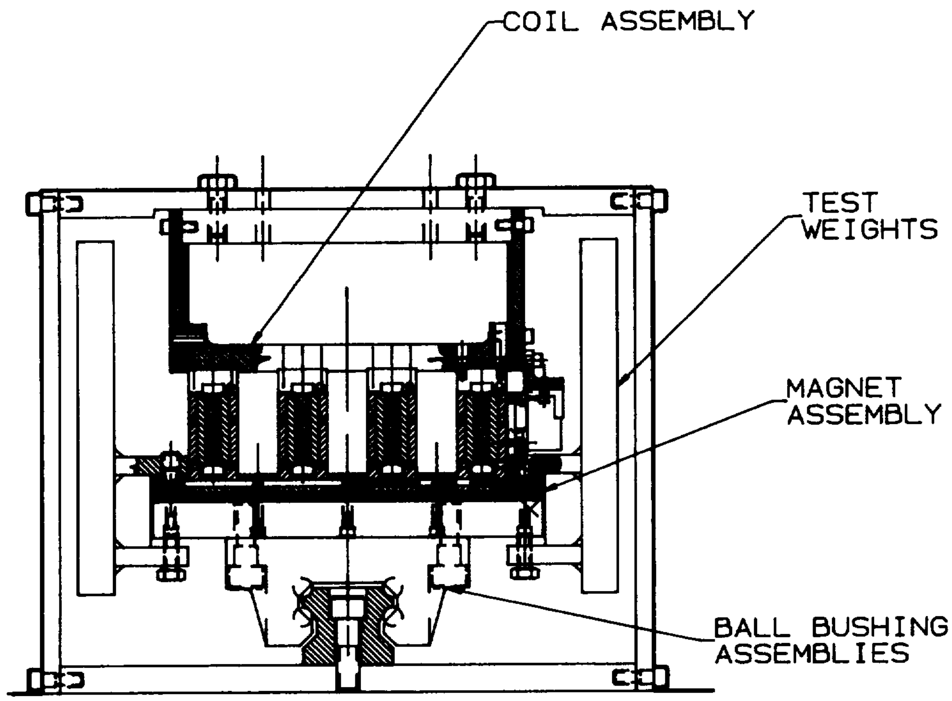


FIGURE 7 MOTOR CHECK-OUT CONFIGURATION

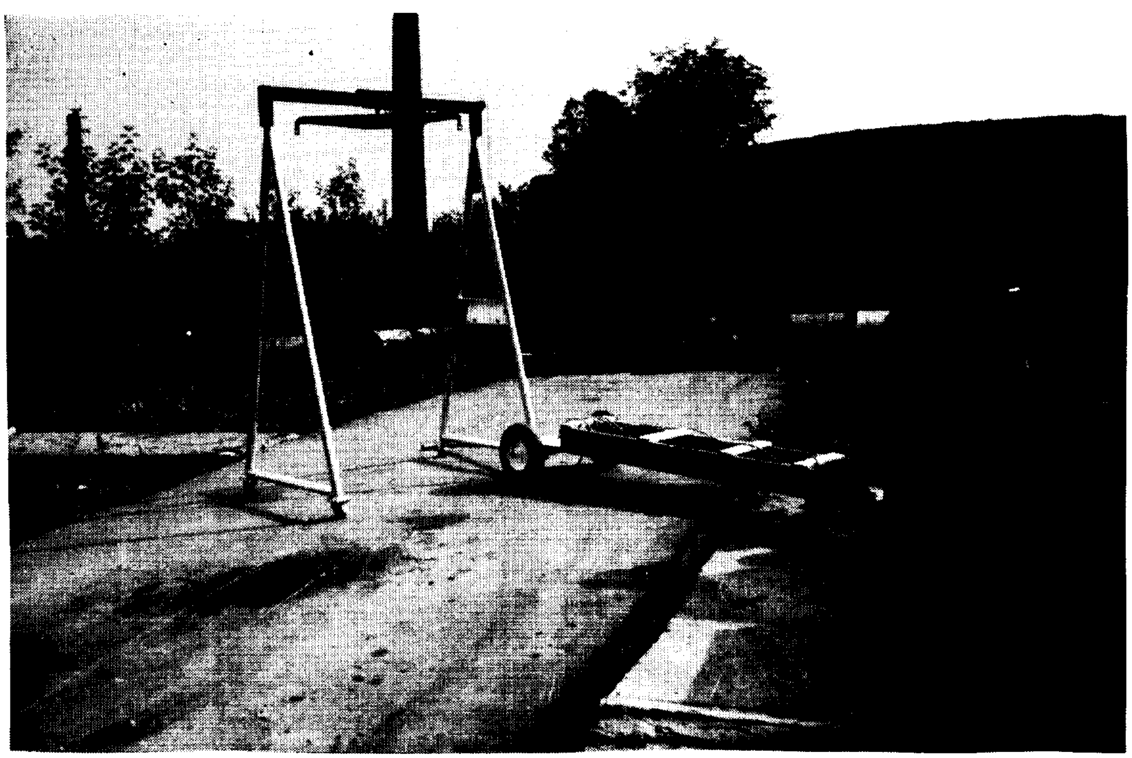


FIGURE 8 HANDLING EQUIPMENT

FIGURE 9 RUNWAY FROM PAVED ROAD TO BUILDING

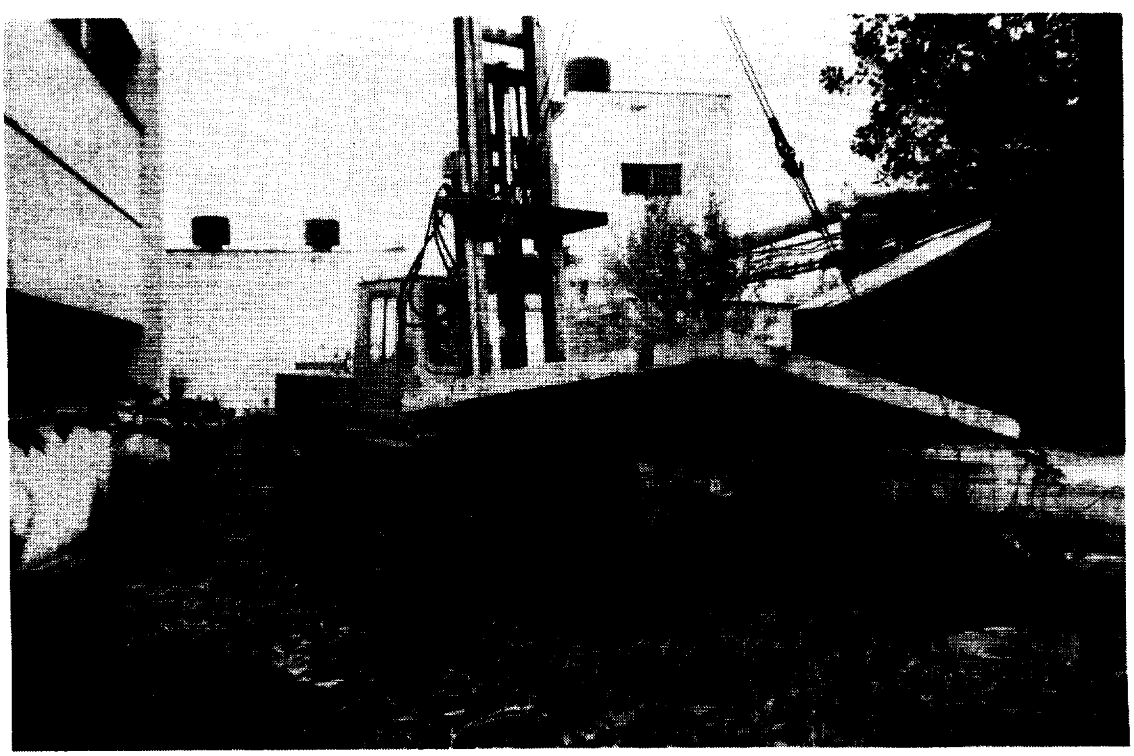


FIGURE 10 TRANSPORTING SLABS TO RUNWAY AND COMPRESSOR SITES

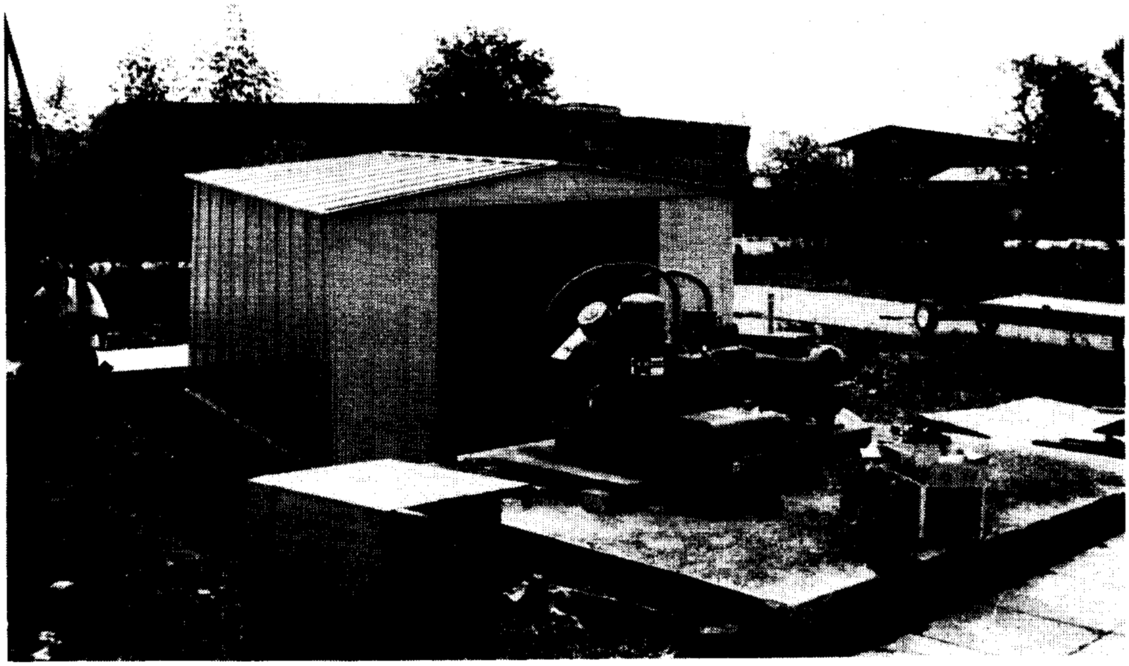


FIGURE 11   COMPRESSOR IN PLACE ON SLAB